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MAGNETOHYDRODYNAMIC INSTABILITY OF SOLAR CORPUSCULAR STREAMS

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ABSTRACT.

This paper considers the flow of solar corpuscular streams in the interplanetary gas. It is shown that the streams are unstable relative to magnetohydrodynamic perturbations. This instability is the result of interaction of these streams with the plasma and the magnetic field of the solar supercorona. Comparison is made between the theoretical and experimental data.

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During the experimental investigations on the scattering of radiowaves received on the ground from the source of cosmic radio emission from Taurus A during its concealing by solar supercorona, the presence of inhomogenous cloudy structure of ionized gas was revealed at distances of 4 — 30 $R_{\odot}$ from the Sun [1 — 4]. An assumption was made in references [1, 3] that the observed inhomogeneities in the electron concentration constitute plasma clouds in solar corpuscular streams. In connection with this it is interesting to ascertain the nature of the mechanism of formation of these streams' cloudy structure. Such stream inhomogeneity must be taken into account when considering their action on Earth's exosphere. As is well known, the latter induces various geomagnetic disturbances.

* Magnitogidrodinamicheskaya neustoychivost' solnechnykh korpuskulyarnykh potokov.

Reference [4 — 9] are devoted to theoretical and experimental study of dynamics of solar corpuscular streams. The results of reserach in active regions of the Sun, wherefrom solar corpuscular streams are ejected, are brought out in reference [5]. The mechanism of their action on the Earth's exosphere is discussed in [6 — 9]. Let us note that the question of stream escape from the active regions of the Sun is not considered in the present work. Neither is the question of their effect upon the Earth's exosphere. Finally, the stream's flow in the interplanetary medium was studied in [10]. Conclusions was reached in this work that the stream is stable relative to plasma oscillations (electrostatic stability). It is noted that this stream will also be stable in the presence of a radial solar magnetic field, thus longitudinal relative to the stream. This assertion is in our opinion incorrect, and it will be shown in the following that the corpuscular streams are unstable relative to magnetohydrodynamic perturbations, when they flow in an interplanetary medium situated within the Sun's magnetic field.

Solar corpuscular streams constitute a strongly ionized monoatomic hydrogenous gas, The degree of gas ionization in the streams in near 100 percent [11]. The velocity of particle flow in corpuscular streams have a very broad spectrum [12]. However, in the subsequent we shall be interested in the nonrelativistic particles of comparatively low energy, which by their concentration constitute the main component of corpuscular streams, and exert a strong effect upon the geomagnetic field. Their velocities usually lay within the 100 — 1000 km/sec range. It is customary to estimate that the concentration of corpuscules having such velocities is equal to $10 - 10^4$ cm^{-3} [4, 8, 10, 11, 12]. After their escape from the corona the streams flow in interplanetary space, which constitutes a strongly ionized gas with a high kinetic temperature.

According to Shklovskiy's estimates the concentration of charged particles on Earth's orbit is $N \lesssim 30 - 200 \text{ cm}^{-3}$, that of neutral particles – $N_m \sim 0.5 \text{ cm}^{-3}$, and temperature of the gas T is more or less $10\,000^{\circ}$ K [11, 21].

Observations have shown that there exists in the solar supercorona a magnetic field, whose lines of force are stretched in a radial direction from the Sun [13]. This "radial" magnetic field has been revealed at distances from 5 to 30 $R_{\odot}$ in the Sun's supercorona. Thus, solar corpuscular streams flow in the interplanetary gas along the lines of force of the Sun's magnetic field *

Let us show that during their motion in the supercorona solar corpuscular streams are unstable relative to magnetohydrodynamic perturbations. Earlier we have considered the problem of flow of a fully ionized gas through a fixed plasma in the presence of a magnetic field directed along the flow velocity of the stream. It was then established that, provided specific conditions are fulfilled, a magnetohydrodynamic instability of the system stream – fixed plasma is observed [14, 15]. The indicated instability is revealed by the fact that one of the normal waves in the system grows on in time. Unfortunatley, it is impossible to answer quite specifically the question of the character acquired by plasma flow as a result of instability, as is usually the case within the framework of linear theory of perturbations. Nevertheless, we may assert on the basis of experiments on magnetohydrodynamic instability, that electron concentration irregularities will appear in the stream, and that consequently it will have a cloudy structure.

We shall estimate that the quasineutral plasma is fully ionized in the stream and in the supercorona. Because of their smallness, let us neglect the collisions between electrons and ions in a quiescent as well as in a flowing stream plasma.

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* It is quite possible that the cause of line of force stretching of the heliomagnetic field lies in the hydromagnetic extrusion of the Sun's field by the head of the solar corpuscular stream.

In this case the interaction between charged particles in the stream and supercorona plasmas is realized only through self-consistent electromagnetic fields. Assume that a stream flows with a velocity V_0 in the direction of the lines of force of a "radial" magnetic field of the Sun H_0. Then the linearized system of equations describing the electromagnetic processes in the stream and in the interplanetary plasma will have the following form [14] :

$$\frac{\partial \mathbf{j}_s}{\partial t} + (\mathbf{V}_0 \nabla)\, \mathbf{j}_s + \omega_H\, [\mathbf{j}_s \vec{\tau}] = \frac{e^2 N_s}{m_e}\left(\mathbf{E} + \frac{1}{c}[\mathbf{V}_0 \mathbf{h}] + \frac{1}{c}[\mathbf{v}_s \mathbf{H}_0]\right); \quad (1)$$

$$\frac{\partial \mathbf{v}_s}{\partial t} + (\mathbf{V}_0 \nabla)\, \mathbf{v}_s = \frac{1}{\rho_s c}[\mathbf{j}_s \mathbf{H}_0]; \quad (2)$$

$$\frac{\partial \mathbf{j}_p}{\partial t} + \omega_H\, [\mathbf{j}_p \vec{\tau}] = \frac{e^2 N_p}{m_e}\left(\mathbf{E} + \frac{1}{c}[\mathbf{v}_p \mathbf{H}_0]\right); \quad (3)$$

$$\frac{\partial \mathbf{v}_p}{\partial t} = \frac{1}{\rho_p c}[\mathbf{j}_p \mathbf{H}_0]; \quad (4)$$

$$\operatorname{rot} \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{h}}{\partial t}; \quad (5)$$

$$\nabla^2 \mathbf{E} - \operatorname{grad}\operatorname{div} \vec{\mathbf{E}} - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial (\mathbf{j}_p + \mathbf{j}_s)}{\partial t}. \quad (6)$$

Here $\mathbf{j}, \mathbf{v}, \rho = m_i N$ are the density of the electric current, the velocity and density of the ionized gas mass ; $\omega_H = eH_0/m_e c$ is the electron gyrofrequency in the solar magnetic field; $\vec{\tau}$ is the unitary vector of this field; N is the concentration of the plasma; m_e and m_i are respectively the masses of the electron and ion; $\mathbf{E}$ and $\vec{h}$ are respectively the strength of the electric field and the intensity of the magnetic field. The little signs s and p are respectively related to quantities in the stream and in the stationary plasma. Equations (2) and (4) are plasma equations of motion, and (1) and (3) express the generalized Ohm law in the indicated media. Despite the high temperature, the speed of sound is much lower in the given case than the Alfvén wave velocity $V_A = H_0/\sqrt{4\pi\rho}$ That is why we neglect the accounting of pressure forces in the equations of motion. The possibility of utilizing the magnetohydrodynamic approach to the problem instead of more sequential kinetic equation method, is justified by the fact that we are expected to deal with motions of much larger scales than the ion gyroradius [16, 17].

From the system of equations (1) — (6) we may obtain the dispersion correlation for plane electromagnetic waves propagating along the stream. For that pruorpose we estimate all the quantities to be changing along the law exp i (ωt — kz), where ω and k are the frequency and the wave number, the axis z being directed along the magnetic field. In this case the dispersion equation has the form [14, 15] :

$$\omega^2 - c^2k^2 = \frac{\omega_{se}^2 (\omega - kV_0)}{\omega - kV_0 \mp \omega_e - \omega_e\omega_i/(\omega - kV_0)} + \frac{\omega_{pe}^2\omega}{\omega \mp \omega_e - \omega_e\omega_i/\omega}, \qquad (7)$$

where $\omega_{se} = (4\pi e^2 N_s/m_e)^{1/2}$ $\omega_{pe} = (4\pi e^2 N_p/m_e)^{1/2}$ are the plasma frequencies of electrons in the stream and in the stationary plasma $\omega_i = eH_0/m_i c$ is the ion gyrofrequency. The sign (+) corresponds to the ordinary wave, the sign (—) — to the extraordinary. Equation (7) describes only the propagation of transverse electromagnetic waves. In the absence of a stream, when $\omega_{se} = 0$, the equation (7) transfers into the well known equation for electromagnetic waves propagating in a plasma along the magnetic field [16].

In the standard approximation of the magnetic hydrodynamics (case of low frequencies, when $\omega \ll \omega_i$, considering also that $kV_0 \ll \omega_i$), we obtain from the equation (7) :

$$k^2 = \frac{(\omega - kV_0)^2}{V_{As}^2} + \frac{\omega^2}{V_{Ap}^2}, \qquad (8)$$

where Alfvén wave velocities V_{As} and V_{Ap} are introduced:

$$V_{As}^2 = c^2\frac{\omega_e\omega_i}{\omega_{se}^2} = \frac{H_0^2}{4\pi\rho_s}, \qquad V_{Ap}^2 = \frac{H_0^2}{4\pi\rho_p}. \qquad (9)$$

The solution of the dispersion equation (8) is easy to find and it may be written in the form

$$\frac{\omega}{k} = \frac{V_0 \pm V_A \sqrt{(1 - V_0^2/V_A^2)\, N_p/N_s}}{1 + N_p/N_s}, \qquad (10)$$

where $V_A^2 = V_{As}^2 + V_{Ap}^2$. – A more detailed deduction of these correlations is presented in the works [14, 15]. It follows from formula (10) that under the condition whereby the velocity of the solar corpuscular flow V_0 exceeds that of the Alfvén wave V_A, there appear in the system stream – interplanetary medium waves growing with time, i.e. the system becomes unstable. A similar instability criterion is encountered in magnetic hydrodynamics when investigating tangential breaks [18]. Consequently if the stream forms a flooded jet-type flow while moving in interplanetary gas, the superficial boundary of that jet will also be unstable relative to magnetohydrodynamic perturbations.*

Therefore, the condition of magnetohydrodynamic instability of solar corpuscular streams has a very simple form:

$$V_0 > V_A = \frac{H_0}{\sqrt{4\pi\rho}}. \qquad (11)$$

Here we introduced the ion mass density in the system stream – interplanetary medium:

$$\frac{1}{\rho} = \frac{1}{\rho_s} + \frac{1}{\rho_p}. \qquad (12)$$

The wave's accretion factor in time τ may be found from the expression (10)

$$\gamma = kV_0 \frac{\sqrt{N_p N_s}}{N_p + N_s}. \qquad (13)$$

It is obvious that γ has a maximum at $N_p = N_s$, i.e. in the case when the concentration in the stream is equal to plasma concentration in in the interplanetary medium. At $N_p = N_s$ we shall obtain $\gamma_{max} = kV_0/2$. The time τ of stream's breakingup into separate clouds may be estimated approximately using (13):

$$\tau = \frac{1}{\gamma} = \frac{N_p + N_s}{kV_0 \sqrt{N_p N_s}}, \qquad (14)$$

τ being minimum in the case when $N_p = N_s$.

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* see infrapag.note next page

Before effecting estimates of the above indicated parameters of instability, it is appropriate to voice certain remarks concerning the parameters of the system stream — interplanetary gas. Direct experiments for the determination of density, temperature and also of structure of the streams are currently absent. Because of that, data on the indicated characteristics of streams are obtained from results of indirect experiments, using ta time of their processing various "a priori" assumptions. This makes difficult the conducting of sufficiently strict estimates of parameters of instability, for there is a great spread in the values of, for example, concentrations, obtained by various reserachers. It is related in an equal degree to data on analogus parameters of the interplanetary gas [3 — 13, 19 — 20]. The results of measurements of electron concentration in the solar supercorona at distances ranging from 5 to 20 solar radii from the surface of the Sun are brought out in reference [19]. Thus, for example, at $R = 5 R_{\odot}$ the concentration of electrons $N_p \simeq 10^5$ cm^{-3}, and at $R = 20 R_{\odot}$, $N_p \simeq 5 \cdot 10^3$ cm^{-3}. According to estimates of works [11, 21], $N_p \simeq 30 - 200$ cm^{-3} on the orbit of the Earth.

It is admitted in most of the works with reference to physics of solar corpuscular streams that the plasma concentration in them has a magnitude of $10^2 - 10^4$ cm^{-3} even on the Earth's orbit. We shall consider that such is the concentration of streams in the supercorona, i.e. at distances $R \leqslant 30 R_{\odot}$. The streams' flow velocity is measured with more precision. It usually ranges within the 100 — 1000 km/sec limits. The chemical composition of the interplanetary space and of the streams is considered identical, since the Sun is the probable source of interplanetary gas [11]. It is basically a proton-electron gas. As pointed out earlier, the magnetic field of the Sun has a radial direction in the supercorona, i.e. the lines of force are stretched along the streams.

* from the preceding page.- At the same time all the plasma within the stream of radius R must move with a velocity V_0 .

According to the estimates brought out in [12, 13], the magnetic field of the Sun has a magnitude $H_0 \sim 3 \cdot 10^{-2}$ gauss at $R = 3R_\odot$, and at a distance of 1 a.e. $H_0 \sim 10^{-5}$ gauss. This means in particular that the magnetic field decreases slower with the distance from the Sun than $H' = H_\odot (R_\odot/R)^3$.

After these preliminary remarks let us pass to estimates. At distances from the Sun $R > 5R_\odot$ the indispensable condition (11) of instability is fulfilled for streams with a velocity $V_0 = 100 - 1000$ km /s and a concentration $N_s = 10^2 - 10^4$ cm^{-3}. Indeed, for $R = 5R_\odot$, $N_p \simeq 10^5$ cm^{-3}, $H_0 \simeq 3 \cdot 10^{-2}$ – gauss and consequently $V_A \simeq \simeq V_{AS} = 700$ km/sec and $V_A = 7000$ km/sec for the respective concentrations in the stream $N_s = 10^4$ and 10^2 cm^{-3}. As the distance from the surface of the Sun increases, V_A decreases and the condition (11) is easier to satisfy. Thus at the distance $R = 1$ a.e. when one may estimate $N_p \sim 100$ cm^{-3}, $H_0 \sim 10^{-5}$ gauss, it is easy to obtain that $V_A \sim 2$ km/sec and $V_0 \gg V_A$. Consequently, the condition for magnetohydrodynamic instability is fulfilled everywhere in the space between the Earth and the Sun. Utilizing the inequality $kV_0 < \omega_i$, one may estimate the minimum length of the growing wave

$$\lambda_m = 2\pi V_0/\omega_i.$$

At $R = 5R_\odot$ and $\omega_i \sim 300$ sec^{-1} we find that $\lambda_m > 5 - 10$ km, while for $R = 1$ a.e. $\lambda_m > 1500 - 150\,000$ km. From experimental data for the solar supercorona the dimensions of inhomogeneities $l \sim 1 - 10^5$ km [1 – 4]. There are indications to the effect that separate plasma clouds move with peculiar velocities of 10^2 to 10^3 km/sec [4].

The time necessary for the disintegration of a stream into separate clouds may be estimated by using formula (14). It is minimum in the region where N_p — N_s. From data on electron density in the supercorona this condition for the streams is fulfilled in the region $10\ R_{\odot} \leqslant R \leqslant 100 R_{\odot}$ [19]. At the same time $\tau_{min} = \lambda/\pi V_0$. In the indicated region $\omega_i \sim 1\ sec^{-1}$, $\lambda_{min} \sim 600 - 6000$ km, and consequently τ_{min} is of the order of a few seconds. On the other hand the time necessary for the stream to cover a distance of 20 $R_{\odot}$ is of the order of 10 hours. This time is quite sufficient to make the stream unstable and to break it up into separate clouds. Farther away, in the interplanetary space, it will obviously move in the form of a nonuniform cloud jet and the indicated dimensions of separate clouds. As pointed out earlier, nothing can be said about the shape of clouds, the fluctuations of electron concentration, for the quantitative consideration of these questions lies beyond the limits of the linear theory of perturbations.

The cloudy, inhomogenous structure of the streams must be taken into account when considering the question of their effect on the Earth's exosphere. It is possible that the impact action of separate clouds of the stream conditions the constrained exosphere oscillations of micropulsation type.

****** THE END ******

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